

## TWO STAGE COPROCESSING OF WASTE TIRES AND COAL

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**Keywords:** waste tires, coal, coliquefaction, coprocessing

### INTRODUCTION

Waste tires present an insidious waste disposal problem since piles of waste tires often attract rodents and other varmints and frequently burn. Recent use of ground waste tires as a fill material for roads has resulted in oil being released from the tire after weathering and the tire fill erupting into flames. Therefore, safe and healthy disposal of waste tires is necessary and needs immediate attention since the Department of Energy has reported that 350 million waste tires are disposed of each year in the United States. A number of safe and useful waste tire processing technologies have been developed as alternatives to disposing in landfills. Waste tires have been used as fuel to generate electricity<sup>1</sup>, as filler in asphalt road pavement,<sup>2</sup> and as raw material for secondary product production.<sup>3</sup> Waste tire pyrolysis<sup>4-6</sup> and liquefaction<sup>7-12</sup> are two technologies that can be applied to waste tires to produce fuels and chemical feedstock, thereby recycling the hydrocarbon base.

Several pyrolysis methods are being developed at pilot or industrial scale.<sup>4</sup> Cypres et al.<sup>4</sup> investigated the effect of pyrolysis conditions on the liquid product and found an increase of naphthalene and benzene with a decrease of the liquid fraction as the residence time increased. Merchant et al.<sup>5</sup> recovered solid material, primarily consisting of carbon black, from waste tire pyrolysis, activated the material, and used it for waste water treatment. Recently, Conesa et al.<sup>6</sup> examined gas production from scrap tires pyrolysis in a fluidized sand bed reactor. The yield of total gas was reported to increase in the range of 600-800 °C from 6.3 to 37.1%.

Waste tire liquefaction has been actively investigated in recent years. Farcasiu et al.<sup>7</sup> indicated that coprocessing waste tire with coal was beneficial for enhancing coal conversion. Liu et al.<sup>8</sup> investigated the liquefaction of coal and waste tire individually and compared the results to that of simultaneously coprocessing the two materials. The conversion obtained from the coprocessing reactions was greater than that achieved from combining the individual reactions. Orr et al.<sup>9</sup> also observed synergism in reactions where there was a 10 to 30% loading of waste tires to coal and the reaction occurred at 350 °C and in reactions at 430 °C at almost all loadings levels of waste tires. Tang and Curtis<sup>10</sup> performed thermal and catalytic coprocessing of waste tires and coal using waste tires from two sources and coals of three different ranks. The bituminous coals yielded higher conversions than either subbituminous coal or lignite when coprocessed with waste tire. Catalytic coprocessing of waste tires with coal using slurry phase hydrogenation catalysts increased conversion of the total system and the coal within the system compared to the conversions obtained in thermal reactions. Orr et al.<sup>11</sup> coprocessed Blind Canyon coal with ground waste tire particles and vacuum pyrolyzed tire oil (PTO), respectively. Coprocessing of coal with PTO yielded higher coal conversion than coprocessing with ground waste tire particles. Badger et al.<sup>12</sup> evaluated hydrogen transfer in coal/oil coprocessing by coprocessing coal with heavy oil (petroleum) distillates (HOD) and pyrolyzed tire oil (PTO). HOD, being highly aliphatic, did not show any H-donation capability. By contrast, PTO, being highly aromatic and containing substantial phenanthrenes and substituted phenanthrenes but very little hydroaromatic compounds, could be induced to transfer hydrogen by hydrogen shuttling. PTO was more effective for dissolving coal after being prehydrogenated and, thereby, containing more hydroaromatic compounds.

The objective of the current research was to investigate the effect of two stage processing of waste tires and coal. The first stage served as a reaction medium by which waste tires were converted to liquids and the solids and where carbon black and other minerals can be removed from the system. In the second stage, the liquefied waste tire served as a solvent for coal and was coprocessed with coal under reaction conditions that were favorable for liquefying of coal and upgrading of coal liquids. Reaction conditions for producing high quality products from both reactions were examined. Both slurry phase and supported catalysts were used.

### EXPERIMENTAL

**Materials.** Two stage reactions were performed by dissolving waste tires in waste oil in the first stage. The carbon black was removed from the liquid by filtration. The waste tire/oil liquid was used as the solvent for coal in the second stage. The waste tire used was supplied by Rouse Rubber industries, Vicksburg, MS. The waste oil was provided by Auburn Waste Oil Reprocessing Lab. The two coals utilized in this research were Beulah Zap lignite and Wyodak Anderson subbituminous coal, both of which were obtained from the Argonne Premium Coal Sample Bank.

Catalytic reactions were performed using slurry phase hydrotreating catalyst, molybdenum naphthenate (MoNaph)(6% Mo), obtained from Shepherd Chemical. Elemental sulfur obtained from Aldrich was added to the catalytic reactions with MoNaph. A supported hydrotreating catalyst, NiMo/Al<sub>2</sub>O<sub>3</sub>(SNiMo), supplied by Shell, was also used in this research. The catalyst was presulfided

prior to reaction by purging the catalyst with  $N_2$  at 300 °C for 1 hr, then subjecting the catalyst to 10.1%  $H_2S/H_2$  with a flow rate of 60 ml/min at 225 °C for 1 hr, followed by 315 °C for two hr, and then 370 °C for 1 hr.

**Reaction Procedures.** The first stage coliquefaction reactions of waste tires with waste oil were performed in approximately 60 cm<sup>3</sup> stainless steel tubular microreactors at 400 °C for 30 min.  $H_2$  or  $N_2$  was introduced at 6.9 MPa at ambient temperature. The total charge to the reactor was 12 g with the waste tire to waste oil ratio being 5:1 or 1:1. In the first stage catalytic coliquefaction reactions, MoNaph was charged at 1000 ppm of active metal per total reactor charge. Elemental sulfur was added to the catalytic reaction with MoNaph in a 3 to 1 stoichiometric ratio of sulfur to metal using the assumption that  $MoS_2$  was formed. For the reactions with SNiMo, the catalyst loading was at 1.5 wt% of SNiMo powder on a total charge basis.

The second stage coprocessing reactions of coal with THF solubles obtained from the first stage reactions were conducted in approximately 20 cm<sup>3</sup> stainless steel microreactors at 400 °C for 30 min. The total charge to the reactor was 5 g with a solvent to moisture and ash free (maf) coal ratio being 1 to 1. In the second stage catalytic coprocessing reactions, the type and loading of the catalysts were the same as the first stage catalytic coliquefaction reactions.

Several reactions were performed by combining waste tire, waste oil, and coal in a single stage reaction at 400 °C for 30 min with initial  $H_2$  pressure at 6.9 MPa. Rouse waste tire and waste oil were added to the reactor with tire to oil ratio at 5 to 1 or 1 to 1 in an amount that would produce 2 g THF solubles when the tire and oil were coliquefied without coal. In catalytic one stage reactions, SNiMo was charged to the reactor together with waste tire, waste oil, and coal at 1.5 wt% of the catalyst on a total charge basis.

**Analysis.** After reaction, gaseous products were determined by weighing the tubular microreactor before and after releasing gaseous products. The liquid and solid products were analyzed by solvent fractionation using sequential extractions of hexane and THF. The organic material that was not soluble in THF was defined as insoluble organic matter or IOM which was ash free.

## RESULTS AND DISCUSSION

Two stage coprocessing of coal and waste tires was investigated to determine if more coal conversion and hexane soluble products could be produced if the waste tire was liquefied prior to contact with coal and the carbon black was removed. The first stage was a coliquefaction of waste tires with waste oil, the waste oil providing a dissolving medium for the tires. Two ratios of waste tires to waste oil, 5:1 and 1:1, were used. At the reaction conditions of 400 °C for 30 min, high conversions to THF soluble materials of the convertible material were obtained regardless of whether the atmosphere was  $H_2$  or  $N_2$ . After reaction, the unconverted material, including carbon black and other mineral constituents in the tire, were removed. The THF soluble liquid was then used as the solvent for the second stage coal reaction.

**Thermal Coprocessing Reactions Using First Stage Liquids as Solvents.** Thermal reactions of Beulah Zap lignite and Wyodak subbituminous coal were performed with first stage liquids as well as waste oil, waste tire, and two hydroaromatic solvents, including tetralin and dihydroanthracene (DHA) as given in Table 2. The reactions with waste tire and/or waste oil were performed in  $H_2$  while the reactions with tetralin and DHA were performed in  $N_2$ . The product distributions and the conversion of the materials were the measure by which the effectiveness of the solvent for liquefaction was determined. The total product distribution and total conversion measured the reactivity of the total system both the solvent and coal. By contrast, the product distribution on a coal basis and the coal conversion removed the effect of the solvent on these two measures, thereby describing how the coal itself reacted in the solvent.

The total conversions obtained for Beulah Zap lignite and Wyodak coal second stage reactions with first stage waste tire and oil solvents were similar and ranged from 64.2 to 67.3% for Beulah Zap and 63.9 to 69.2% for Wyodak. The total conversions with DHA and tetralin as solvents were somewhat higher but also similar and gave values of 74.6 and 72.8%, respectively. The total product distribution yields for gases, hexane solubles, and THF solubles were also similar for all of the reactions with waste tire and waste oil first stage liquids. However, tetralin yielded the highest hexane solubles, while DHA yielded the lowest. The reaction with DHA gave the largest amount of THF solubles of any of the reactions.

Coal conversions and, particularly, product distributions based on coal with the solvent effect removed showed more variability than those from the total values. Factors that affected coal conversion included type of coal used, atmosphere used in the first stage reaction, and ratio of waste tires to waste oil used in the first stage. The amount of hexane soluble and THF soluble material produced was also dependent on these factors. For lignite, coal conversion with solvents consisting of 5:1 ratio of waste tires to waste oil was greater than the 1:1 ratio regardless of the type of atmosphere used in the first stage reaction. Coal conversion was also higher when a  $H_2$  atmosphere was used in the first stage rather than a  $N_2$  atmosphere regardless of ratio. The coal conversion ranged from 34.2% for a 5:1 tires to oil ratio in the first stage reacted in  $H_2$  to a low of 25.7% when a 1:1 ratio was reacted in a  $N_2$  atmosphere. The ratio of waste tire to waste oil also strongly affected

the amounts of hexane solubles and THF solubles obtained with a given atmosphere. The higher ratio resulted in less hexane solubles and more THF solubles.

The factors that affected the second stage lignite thermal reaction also affected the Wyodak second stage reaction. Higher conversion was observed with first stage having a 5:1 ratio and when reacted in  $H_2$ . Reactions were performed with the individual reactants as well. Waste tires as a solvent gave a Wyodak conversion of 40.2 % while waste oil yielded 34.1%. The hexane solubles based on coal were higher with the higher ratio of 5:1 and a  $H_2$  atmosphere in the first stage reaction.

Hydrogen donation to coal by solvents derived from waste tires during liquefaction is feasible since these solvents contain aromatic oil that can be hydrogenated to form hydroaromatics during coprocessing. Badger et al. (1994) evaluated H-donation to coal using solvent produced from the pyrolysis of waste tires. The pyrolyzed oil itself was ineffectual in converting coal even in a  $H_2$  environment. Prehydrogenating the waste tire liquids was effectual for H-donation if the extent of prehydrogenation was not too great, since too much hydrogenation decreases the hydrogen donor capability of the solvent. (Badger et al., 1994; Curtis et al., 1981) In the current study, hydrogen donation from liquefied waste tires to coal was evaluated by comparing the coal conversion obtained in a liquefied waste tire/waste oil solvent to that obtained with tetralin and DHA in a  $N_2$  atmosphere. The highest coal conversions, 48.7 and 44.5%, respectively, were achieved with these hydrogen donors, thereby indicating that the waste tire/waste oil solvents were much inferior hydrogen donors.

**Catalytic Two Stage Coprocessing.** The low total and coal conversions obtained from thermal two stage coprocessing clearly showed the need for introducing catalysts into one of the stages. Table 3 presents the conversions and product distributions from two stage reactions with catalysts being introduced separately in the first and second stage. Sulfided  $NiMo/Al_2O_3$  and MoNaph plus excess S catalysts were each added to the second stage of the two stage reaction using Wyodak coal. The total conversion for the SNiMo catalyst ranged from 79.7 to 86.5% while higher total conversions were observed for the second stages with MoNaph + S, ranging from 94.5 to 95.2%. The coal conversion using SNiMo catalysts resulted in higher conversion, which ranged from 61.5 to 73.1%, than the thermal reaction which ranged from 25.6 to 40.5%. The MoNaph was even more effective since reactions with MoNaph + S and coal resulted in coal conversion which ranged from 89.8 to 91.2%. Reactions performed with solvents of the 5:1 ratio of waste tires to waste oil that had been liquefied in a  $H_2$  atmosphere yielded the highest conversions with each catalyst. However, when either catalyst was added to the first stage, neither was effectual resulting in low total conversions of ~68% and coal conversion of ~40 to 41 %. These low two stage conversions showed that adding the catalyst to the first stage resulted in conversion values that were similar to thermal reactions. These results strongly indicated that the catalysts were deactivated by contact with the waste tires while they were being liquefied.

**Comparison of One and Two Stage Coprocessing.** A comparison of one and two stage coprocessing reactions is given in Table 4 where thermal and catalytic reactions of Wyodak coal performed under equivalent conditions but using different staging are given. The catalyst used in the comparison is SNiMo. The separation of the tire liquefaction reaction from the coal liquefaction reaction dramatically improved the efficacy of the catalyst. At a 5:1 ratio of waste tire to waste oil, the thermal conversion was higher in the single stage reaction than in the two stage reaction. However, the addition of the catalyst in the single stage reaction resulted in only minimal improvement of less than 2% conversion, while a substantial increase in conversion (32.6%) was observed when the catalyst was added to second stage of the two stage reaction. In addition, the observation can be made that the less contact between liquefying waste tire and catalyst, the better the overall conversion obtained. The single stage conversions with the catalyst with a waste tire to waste oil ratio of 1:1 were higher than the reactions with ratios of 5:1. These results emphasize the detrimental effect on catalytic activity that resulted from direct contact between the liquefying waste tire and the hydrotreating catalysts.

## SUMMARY AND CONCLUSIONS

The advantage of two stage coprocessing of waste tires with coal was most apparent when a catalyst was used. The introduction of a hydrotreating catalyst in the second stage resulted in improved overall conversion and coal conversion. The slurry phase Mo naphthenate catalyst was more effective than the supported  $NiMo/Al_2O_3$  catalyst when added to the second stage. In the second stage, the catalyst contacted waste tire that had been already liquefied and whose carbon black and mineral constituents had been removed, and, hence, the catalyst suffered less deactivation.

The waste tire itself was a reasonably effective solvent for coal dissolution but did not provide much H-donor capability. The result was clearly observed when the conversions obtained with liquefied waste tires were benchmarked against these obtained with known H-donors. Increased reactivity of the waste tire solvent for coal dissolution may be possible by pyrolyzing and prehydrogenating the waste tire. This research is currently underway.

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**Table 1. Thermal Coliquefaction of Waste Tires with Waste Oil<sup>a</sup>**

Reactants	Ratio (wt)	THF Solubles (wt%)		Conversion (wt%)	
		Total	Tire	Total	Tire
6.9 MPa of H <sub>2</sub> at ambient temperature					
RWT/WO <sup>a</sup>	5:1	94.2±1.2	93.1±1.6	96.2±1.3	95.7±1.4
RWT/WO	1:1	95.5±0.4	92.4±0.5	97.5±0.8	93.5±0.9
6.9 MPa of N <sub>2</sub> at ambient temperature					
RWT/WO	5:1	93.0±1.4	91.5±1.8	95.5±1.5	93.9±1.9
RWT/WO	1:1	94.7±0.9	90.2±1.2	96.6±1.0	91.3±1.0

<sup>a</sup> Coliquefaction reaction conditions: 400°C, at 6.9 MPa H<sub>2</sub> and N<sub>2</sub>, for 30 min, total charge 12 gram with ratio of waste tire to waste oil being 5 to 1 and 1 to 1.

<sup>b</sup> RWT=Rouse waste tire provided by Rouse Company, WO=waste motor oil provided by Auburn Waste Oil Reprocessing Lab.

**Table 2. Thermal Coprocessing Reactions of Coals with the Liquids Obtained by First Stage Coliquefaction of Waste Tire and Waste Oil<sup>a</sup>**

Liquid Source	Coal	Product Distribution (wt%)						Conversion (%)	
		Total			Coal			Total	Coal
		Gas	HEXS <sup>b</sup>	THFS <sup>b</sup>	Gas	HEXS	THFS		
WO <sup>b</sup>	BZ <sup>c</sup>	3.9±0.3	51.1±1.0	12.3±1.1	5.3±0.6	4.8±2.9	24.6±2.7	67.3±2.2	34.7±1.3
RWT/WO 5/1 H <sub>2</sub> <sup>d</sup>		4.9±0.5	44.0±0.8	16.6±1.0	6.9±0.9	3.2±2.3	24.1±2.5	65.5±2.0	34.2±1.1
RWT/WO 1/1 H <sub>2</sub>		4.3±0.2	50.1±1.1	10.1±1.3	6.0±0.5	11.3±3.0	13.0±3.2	64.5±2.5	30.3±1.4
RWT/WO 5/1 N <sub>2</sub>		4.6±0.4	47.3±0.6	13.2±0.9	6.6±0.8	5.8±1.8	18.1±2.3	65.1±1.7	30.5±0.9
RWT/WO 1/1 N <sub>2</sub> <sup>d</sup>		4.8±0.6	54.0±1.3	5.4±0.6	7.2±1.1	15.1±3.4	3.4±1.5	64.2±1.9	25.7±1.6
Tetralin with N <sub>2</sub>	WY <sup>e</sup>	2.1±0.4	63.1±1.6	9.2±0.9	2.3±0.4	28.0±2.0	18.4±1.7	74.6±2.7	48.7±3.4
DHA with N <sub>2</sub>		3.0±0.6	45.4±1.4	24.4±1.1	4.2±1.1	37.6±1.8	2.7±1.3	72.8±2.9	44.5±3.2
RWT		3.2±0.2	51.1±1.0	14.3±0.9	3.8±0.4	16.7±2.3	19.7±1.8	68.6±1.8	40.2±1.9
WO		3.5±0.4	54.9±1.4	8.1±0.8	4.4±0.8	13.8±1.5	15.9±2.0	66.5±2.4	34.1±2.0
RWT/WO 5/1 H <sub>2</sub>		3.4±0.2	54.0±0.7	11.8±0.3	4.1±0.5	21.4±0.9	15.0±0.5	69.2±1.0	40.5±1.4
RWT/WO 1/1 H <sub>2</sub>		3.8±0.3	52.1±1.0	8.4±1.0	5.0±0.5	15.4±1.0	9.5±1.9	64.3±2.0	29.9±2.9
RWT/WO 5/1 N <sub>2</sub>		3.0±0.2	52.5±0.8	11.7±0.8	3.4±0.5	19.7±1.3	14.7±0.9	67.2±1.9	37.8±2.0
RWT/WO 1/1 N <sub>2</sub>		3.6±0.5	52.5±1.2	7.8±0.8	4.6±0.8	12.5±1.1	8.5±1.5	63.9±1.6	25.6±2.5

<sup>a</sup> Reaction conditions: 400°C, 30 min, 6.9 MPa H<sub>2</sub> at ambient temperature, 2 g maf coal, maf coal:solvent=1:1.

<sup>b</sup> HEXS=hexane solubles; THFS=THF soluble and Hexane insolubles;

BZ=Beulah-Zap lignite; WY=Wyodak subbituminous coal; RWT=Rouse waste tire provided by Rouse Company;

WO=waste motor oil supplied by Auburn Waste Oil Reprocessing Lab.

<sup>c</sup> RWT/WO 5/1 H<sub>2</sub> = the liquid(THF solubles) obtained by first stage coliquefaction of Rouse waste tire and waste oil at 400 °C, in 6.9 MPa initial H<sub>2</sub>, at waste tire:waste oil=5:1, for 30 min, then extracting the product with THF;

RWT/WO 1/1 N<sub>2</sub> = the liquid(THF solubles) obtained by first stage coliquefaction of Rouse waste tire and waste oil at 400 °C, in 6.9 MPa initial N<sub>2</sub>, at waste tire:waste oil=1:1, for 30 min, then extracting the product with THF.

**Table 3. Coprocessing Reactions of Wyodak Coal with the Liquids Obtained by Coliquefying Waste Tires and Waste Oils Thermally and Catalytically<sup>a</sup>**

Liquid Source	Catalyst	Product Distribution (wt%)						Conversion (%)	
		Total			Coal			Total	Coal
		GAS	HEXS <sup>a</sup>	THFS <sup>a</sup>	GAS	HEXS	THFS		
Catalyst added in the second stage but not in the first stage									
RWT/WO 5/1 H <sub>2</sub> <sup>c</sup>	SNiMo	4.8±0.8	50.0±1.7	31.7±1.2	7.0±1.6	11.3±3.2	54.8±2.3	86.5±2.8	73.1±3.3
RWT/WO 5/1 N <sub>2</sub>		2.7±0.3	52.7±1.6	24.3±0.6	2.9±0.6	20.1±1.8	38.5±0.8	79.7±1.8	61.5±2.6
RWT/WO 1/1 H <sub>2</sub>		3.9±0.7	52.0±1.6	26.0±1.1	5.1±1.3	18.1±2.8	42.6±2.1	81.9±2.6	65.8±2.9
RWT/WO 5/1 H <sub>2</sub>	MoNaph+S	4.0±0.6	48.6±1.3	42.6±0.9	5.0±1.0	14.6±2.4	71.6±1.7	95.2±2.1	91.2±2.5
RWT/WO 5/1 N <sub>2</sub>		2.6±0.4	53.7±1.9	38.2±1.1	2.8±0.7	23.1±3.4	63.9±1.9	94.5±3.0	89.8±3.4
RWT/WO 1/1 H <sub>2</sub>		3.5±0.7	55.1±1.5	36.3±1.0	4.3±1.3	22.0±2.8	63.8±1.8	94.9±2.6	90.1±3.0
Catalyst added in the first stage but not in the second stage									
RWT/WO 5/1 H <sub>2</sub>	SNiMo	3.2±0.3	52.1±1.2	12.8±1.0	3.6±0.7	20.0±2.3	16.6±1.8	68.1±2.2	40.3±3.0
RWT/WO 5/1 H <sub>2</sub>	MoNaph+S	3.4±0.7	50.5±0.9	15.0±0.7	4.1±1.2	17.0±1.7	20.7±1.5	68.9±1.6	41.8±2.8

<sup>a</sup> Coprocessing Reaction conditions: 400°C, 30 min, 6.9 MPa H<sub>2</sub> and N<sub>2</sub> at ambient temperature, 2 g maf Wyodak coal, maf coal:solvent = 1:1, SNiMo 1.5wt%; MoNaph 1000 ppm Mo, S:Mo=6:1.

<sup>b</sup> HEXS=hexane solubles; THFS= THF soluble and hexane insolubles.

<sup>c</sup> RWT= Rouse waste tire provided by Rouse Company.

<sup>d</sup> WO= waste motor oil supplied by Auburn Waste Oil Reprocessing Lab.

<sup>e</sup> RWT/WO 1/1 in H<sub>2</sub>-the liquid(THFS) obtained by coliquefying Rouse waste tire and waste oil at 400 °C, in 6.9 MPa initial H<sub>2</sub>, at waste tire:waste oil=5:1, for 30 min, then extracting the product with THF. For catalytic coliquefaction, SNiMo(1.5 wt%) and MoNaph+S(1000 ppm, S:Mo=6:1).

**Table 4. Comparison of Single and Two Stage Thermal and Catalytic Coprocessing Reactions of Wyodak Coal with Waste Tire and Waste Oil<sup>a</sup>**

Reactants	Catalyst	Product Distribution (wt%)						Conversion (%)	
		Total			Coal			Total	Coal
		GAS	HEXS <sup>a</sup>	THFS <sup>a</sup>	GAS	HEXS	THFS		
Two Stage Reaction									
WY+(RWT/WO 5/1H <sub>2</sub> ) <sup>a</sup>	None	3.4±0.2	54.0±0.7	11.8±0.3	4.1±0.5	21.4±0.9	15.0±0.5	69.2±1.0	40.5±1.4
WY+(RWT/WO 5/1H <sub>2</sub> )	SNiMo	4.8±0.8	50.0±1.7	31.7±1.2	7.0±1.6	11.3±3.2	54.8±2.3	86.5±2.8	73.1±3.3
WY+(RWT/WO 1/1H <sub>2</sub> )	None	3.8±0.3	52.1±1.0	8.4±1.0	5.0±0.5	15.4±1.9	9.5±1.9	64.3±2.0	29.9±2.9
WY+(RWT/WO 1/1H <sub>2</sub> )	SNiMo	3.9±0.7	52.0±1.6	26.0±1.1	5.1±1.3	18.1±2.8	42.6±2.1	81.9±2.6	65.8±2.9
One Stage Reaction									
WY+RT+WQ(T/O 5/1) <sup>a</sup>	None	5.8±0.5	41.0±1.1	24.0±1.2	5.5±0.6	1.4±0.3	40.9±2.4	70.7±1.3	47.8±2.0
WY+RT+WQ(T/O 5/1)	SNiMo	6.7±0.6	44.7±1.7	22.1±1.4	7.1±1.0	2.4±0.4	39.9±2.1	73.5±1.7	49.5±1.9
WY+RT+WQ(T/O 1/1)	None	5.5±0.2	42.4±1.5	25.5±1.8	5.0±0.8	6.0±0.5	44.6±2.7	73.3±1.9	50.2±2.8
WY+RT+WQ(T/O 1/1)	SNiMo	6.2±0.4	48.0±1.8	22.8±1.5	6.5±1.2	4.6±0.4	42.5±2.1	77.0±2.0	53.6±2.7

<sup>a</sup> Reaction conditions: 400°C, 30 min, 6.9 MPa H<sub>2</sub> at ambient temperature, 2 g maf Wyodak coal, maf coal:solvent(THF solubles) = 1:1.

<sup>b</sup> WY=wyodak coal;

<sup>c</sup> RWT=Rouse waste tire;

<sup>d</sup> WO=waste oil from Auburn Waste Oil Reprocessing Lab.

<sup>e</sup> HEXS=hexane solubles;

<sup>f</sup> THFS= THF solubles;

<sup>g</sup> SNiMo= presulfided NiMo/Al<sub>2</sub>O<sub>3</sub>.

<sup>h</sup> For two stage reactions, (RT/WO 5/1 H<sub>2</sub>)= THF Solubles obtained from the first stage reaction with Rouse waste tire to waste oil ratio of 5 to 1 in H<sub>2</sub>; For one stage reactions, RT+WQ(T/O 5/1)= Rouse waste tire with waste oil at tire to oil ratio of 5 to 1 in an amount that would produce 2 g THF solubles.